

Short range correlations and **intrinsic p_T** from QCD vacuum structure

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with Mark Strikman and Christian Weiss

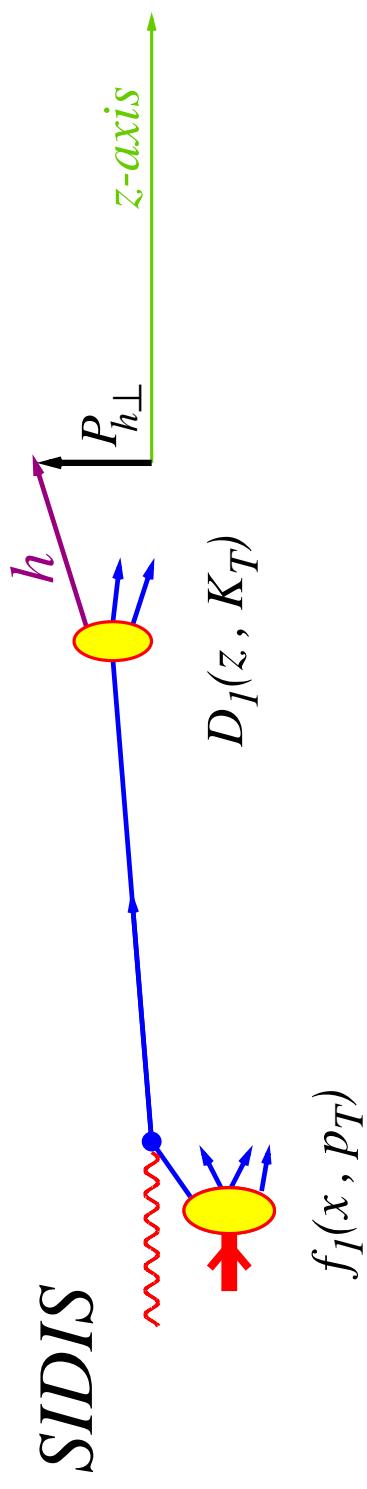
Outline

- introduction: phenomenology & quark models $\longrightarrow p_T$ (of valence quarks)
- chiral quark soliton model p_T of **valence & sea** quarks: 2 scale picture
non-perturbative short-range correlations, QCD vacuum structure
- what do we mean by “**intrinsic**” p_T ? Outlook

1. Introduction

$$\text{TMDS}(x, p_T)$$

\vec{p}_T vector in transverse plane $\perp \vec{e}_z$ (in DIS $\parallel \gamma^*$)
⇒ correlations with nucleon polarization \vec{S}_N , and
quark polarization vector \vec{S}_q ($\gamma^+, \gamma^+ \gamma_5, i\sigma + j\gamma_5$)



Exciting phenomena:

Sivers, Collins effect, transversity, Boer-Mulders function, gear worms, pretzelosity, orbital motion, extractions, predictions, ...

all extremely exciting, but this talk about: $f_1^a(x, \not{p}_T)$ with $\not{p}_T = |\vec{p}_T|$

- most basic, “denominator,” prerequisite for ‘exciting stuff’
- far from well known, though a little bit is known

1.1. Lesson from data and phenomenology:

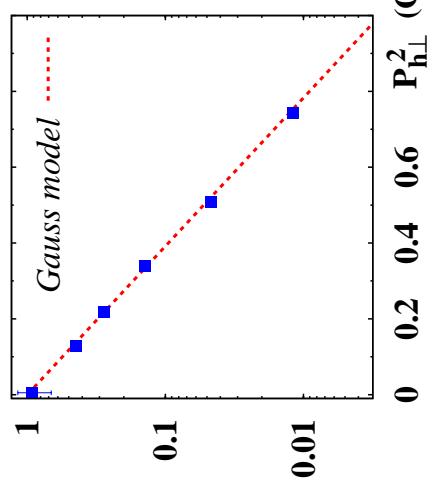
in “practice”
it’s Gaussian:

$$f_1^a(x, p_T) = f_1^a(x) \frac{\exp(-p_T^2 / \langle p_T^2 \rangle)}{\pi \langle p_T^2 \rangle}$$

if: transverse momentum in final state \ll hard scale \rightarrow **effective description!**
PS, Teckentrup, Metz PRD81 (2010) 094019; D’Alesio & Murgia (2004)

Example 1: $R(P_{h\perp}^2) \equiv \frac{d\sigma_{UU}(P_{h\perp}) / dP_{h\perp}^2}{d\sigma_{UU}(0) / dP_{h\perp}^2}$ for π^+ from proton, $x = 0.24$,
 $z = 0.3$, $Q^2 = 2.37 \text{ GeV}^2$

$$R(P_{h\perp}^2)$$



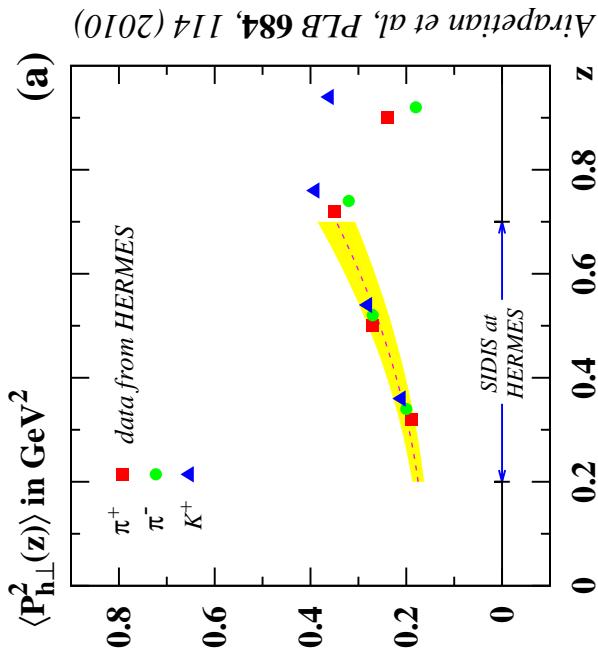
it works!

though $z = 0.3$
with $E_{\text{beam}} = 5.75 \text{ GeV}$
 $\Rightarrow \pi^+$ from struck quark,
or: target fragmentation
(“fracture functions”)

CLAS (Osipenko et al, PRD 80 (2009) 032004)
(compatible with Hall C Mkrtchyan et al, PLB 665, 20 (2008))

Example 2: HERMES

$$\langle Q^2 \rangle = 2.5 \text{ GeV}^2, \langle x \rangle = 0.09$$



$$\langle P_{h\perp}^2(z) \rangle \quad \text{Gauss!} \quad z^2 \langle p_T^2 \rangle + \langle K_T^2 \rangle$$

compatible with x, z -independent

$$\begin{aligned} \langle p_T^2 \rangle &= (0.38 \pm 0.06) \text{ GeV}^2 & \text{in} & f_1^a(x, p_T) \\ \langle K_T^2 \rangle &= (0.16 \pm 0.01) \text{ GeV}^2 & \text{in} & D_1^a(z, K_T) \end{aligned}$$

PS, Teckentrup, Metz PRD81 (2010) 094019

it works!

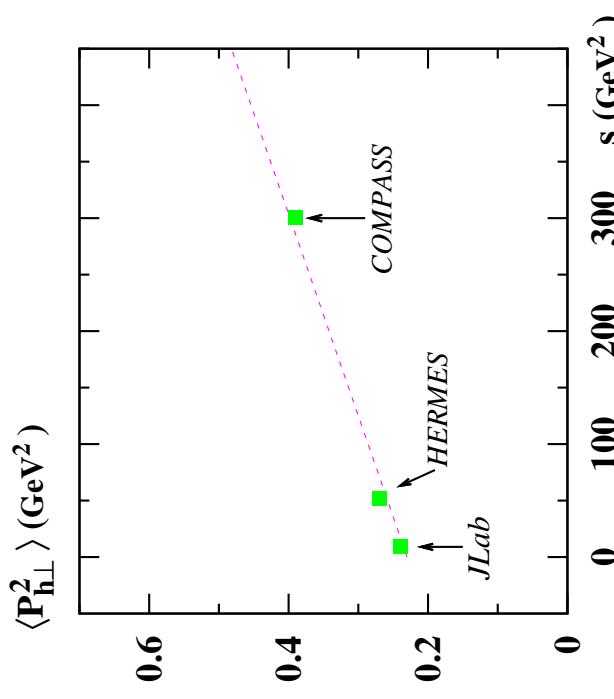
Important: no difference between π^\pm, K^+
no indications for flavor dependence of $\langle p_T^2 \rangle, \langle K_T^2 \rangle$

→ because $\langle p_T^2 \rangle$ really flavor-independent?

→ or because valence quarks dominate $\langle P_{h\perp} \rangle$?

even more important (but not subject of this talk)

Gauss works, but widths **energy-dependent** (!)



p_T -broadening, well known from DY
Collins, Soper, Sterman NPB250 (1985) 199
Landry et al, PRD67 (2003) 073016
(electro-weak bosons, Tevatron)
Aybat, Rogers arXiv:1101.5057

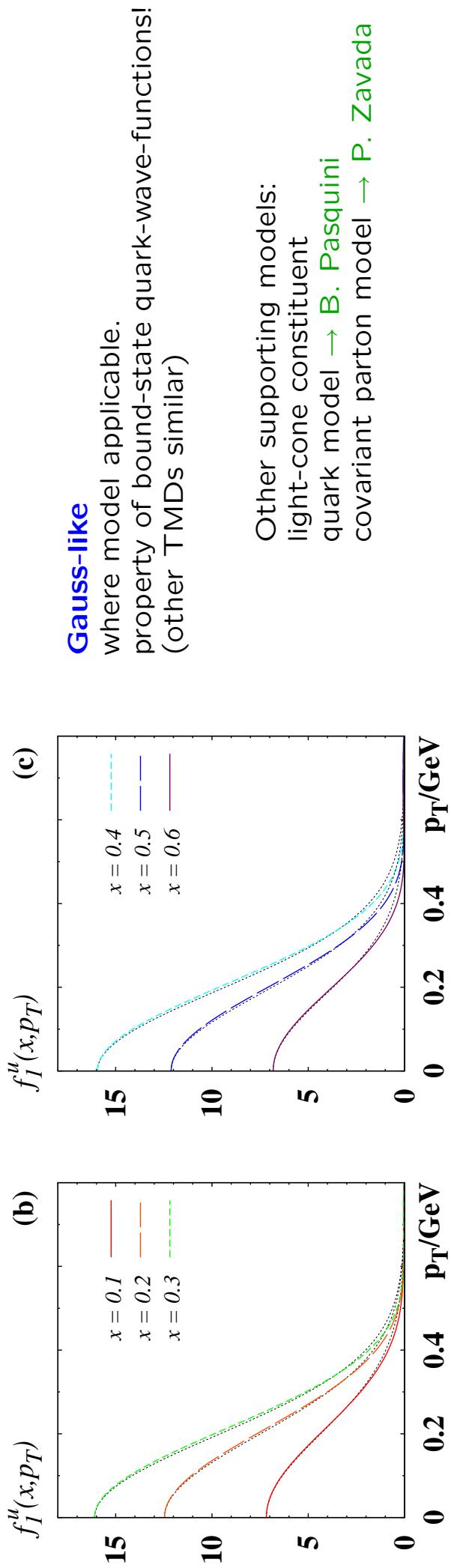
indication for p_T -broadening in SIDIS
(in current, data-delivering experiments)

at $z \simeq 0.5$
JLab (op. cit.),
HERMES (op. cit.),
COMPASS (J.-F. Rojotte,
Spin Praha proc. arXiv:1008.5125)

Needs to be carefully taken into account!
(in SIDIS, also Drell-Yan and RHIC)
first steps done → talk by Ted Rogers

1.2 Lesson from quark models

Example bag model: 3 relativistic, free, massless quarks **confined** in a cavity
 Chodos, Jaffe, Johnson, Thorn, Weisskopf, PRD **9**, 3471 (1974)



colored solid lines: **exact** $f_1^q(x, p_T)$ from bag

dotted black lines: **Gauss** approx. in bag model

Avakian, Efremov, PS, Yuan, PRD **81**, 074035 (2010)

Observation:

- SIDIS, DY data compatible with Gauss Ansatz
- Gaussian widths show no indication of flavor dependence
- but available data are dominated by valence quark effects
- quark models ('bound state wave-funct.') support Gauss behaviour

Question:

- could p_T of sea quarks be different?
- if so, why?

Address question in: chiral quark soliton model (χ QSM)
based on QCD vacuum structure

2. Chiral quark soliton model

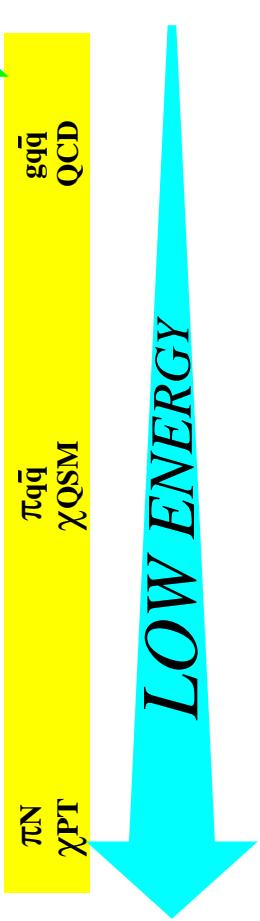
Diakonov, Petrov, Pobylitsa 1984, 1986

- “interpolates” (uses q, \bar{q} , Goldstone bosons)

- spontaneous χ symm. breaking, from instanton liquid model of QCD vacuum: $\rho_{\text{av}} / R_{\text{av}} \sim \frac{1}{3}$

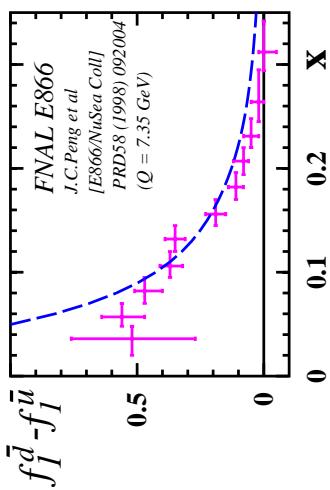
- $\mathcal{L}_{\text{eff}} = \bar{\psi} \left(i \not{\partial} + M \exp(i \gamma_5 \tau^a \pi^a / F_\pi) \right) \psi$ for $p \lesssim \rho_{\text{av}}^{-1} \simeq 600 \text{ MeV}$
“constituent mass” $M = 350 \text{ MeV}$ (or $f_{\pi q\bar{q}} = \frac{M}{F_\pi}$)

- realization of large N_c picture (Witten 1979):
soliton of chiral field $U = \exp(i \tau^a \pi^a)$
 - calculate form factors, GPDs, PDFs, ...
in systematic $1/N_c$ expansion
 - successfull, consistent effective field theory
(positivity, polynomiality, stability, sum rules)
-

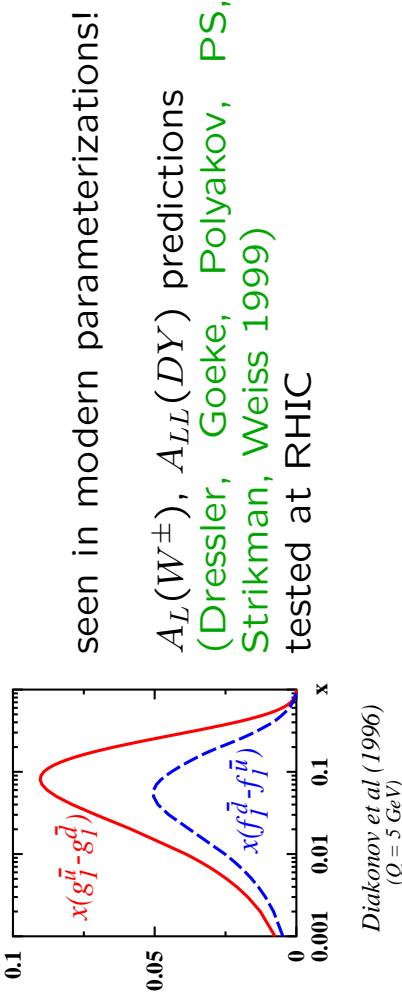


success: no free parameters, describes nucleon properties within (10–30) %

- explains flavor asymmetry in unpolarized sea $f_1^{\bar{d}} > f_1^{\bar{u}}$ ✓



from Polylytsa et al (1998)

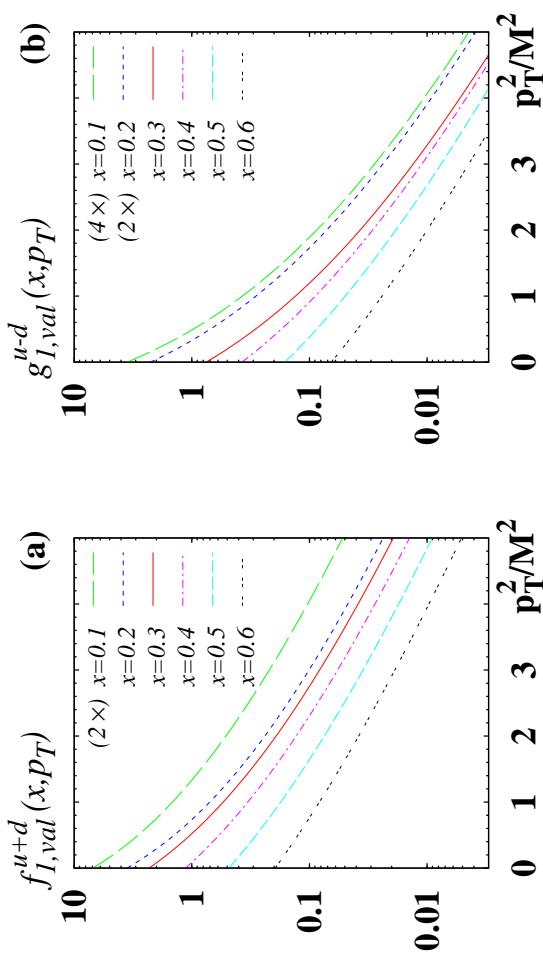


- recently: **TMDs** (Wakamatsu 2009 f_1^{u+d} , PS, Strikman, Weiss 2011 f_1^{u+d}, g_1^{u-d})

Important: p_T dimension-full quantity
→ **interplay of 2 non-perturbative scales:**

- small scale: constituent quark mass M
 - large scale: vacuum structure ρ_{av}^{-1}
- **scales very different:** $M \rho_{\text{av}} \ll 1$
(‘diluteness’ of instanton medium)

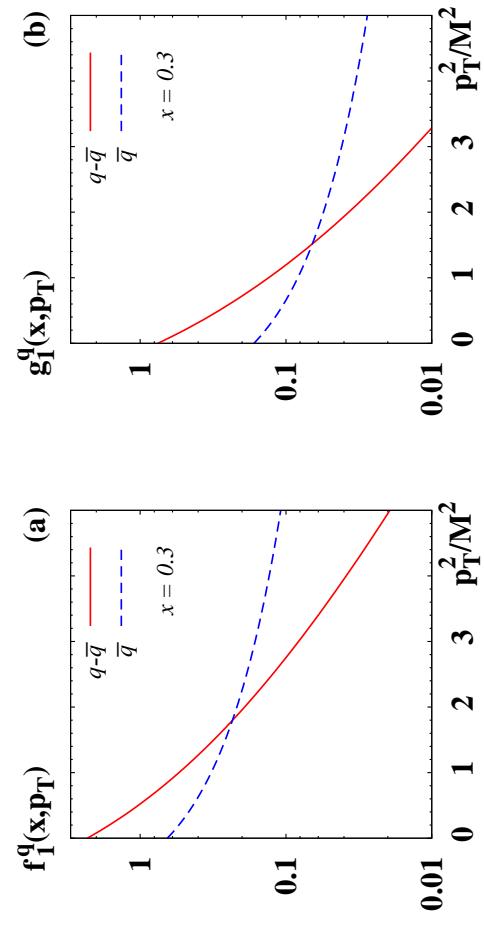
• valence quarks



\sim Gaussian, $\langle p_T^2 \rangle_{\text{val}} \sim M^2$

dominated by bound state,
qualitatively similar to bag

• sea quarks (!!)



\sim power-like, $\langle p_T^2 \rangle_{\text{sea}} \sim \rho_{\text{av}}^{-2}$

due to short range correlations
QCD (instanton) vacuum effect
 χ symmetry breaking

in leading order chiral expansion $\mathcal{O}(\nabla U \nabla U^\dagger)$: $f_1^{\bar{q}}(x, p_T) \approx f_1^{\bar{q}}(x) \frac{C_1}{M^2 + p_T^2}$

$$\Rightarrow f_1^{\bar{q}}(x, p_T) \approx f_1^{\bar{q}}(x) \frac{C_1}{p_T^2} \quad \text{for } M \ll p_T \lesssim \rho_{\text{av}}^{-1} \quad \text{with } C_1 = \frac{2N_c M^2}{(2\pi)^3 F_\pi^2}$$

analog for $q = val + \bar{q}$, analog for g_1^a (pol. independent)

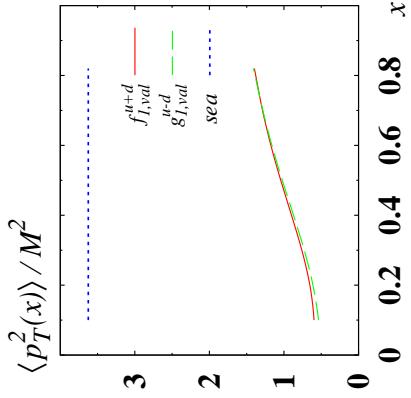
but: transversity same valence-type behavior for q, \bar{q}
because $f_1^a / g_1^a \leftrightarrow \text{Vector/Axial-current}, \chi\text{-symm. (?)}$

$$\mu = \rho_{\text{av}}^{-1}$$

$$\Rightarrow f_1^a(x) \Big|_{\mu = \rho_{\text{av}}^{-1}} = \int d^2 p_T f_1^a(x, p_T) \quad (\text{log. divergence, no problem})$$

$$f_1^a, g_1^a: \quad \langle p_T^2 \rangle_{\text{sea}} = - \frac{\langle \bar{\psi} \psi \rangle M}{2F_\pi^2} \quad (\text{quadr. divergence}) \rightarrow \chi \text{ symm. breaking}$$

$$\text{numerically } \langle p_T^2 \rangle_{\text{sea}} \sim 3 \langle p_T^2 \rangle_{\text{val}} !!!$$

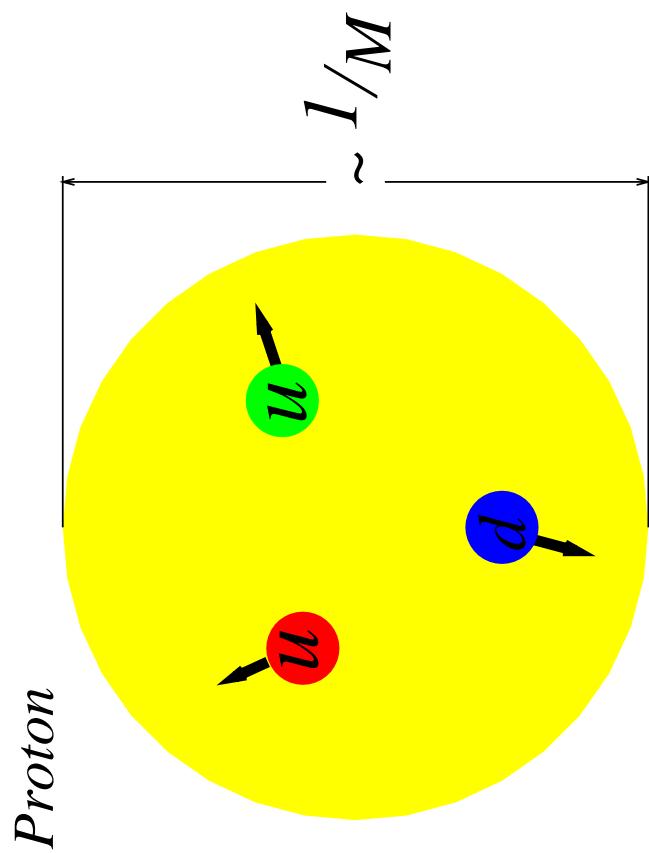


observe at:

EIC, COMPASS, JLab 12.
($K^+ = u\bar{s}$ vs. $K^- = \bar{u}s$)
Drell-Yan pp vs. $p\bar{p}$ (GSI Fair)

Picture with constituent quark degrees of freedom

(bag model, light-cone constituent model, . . . , bound-state in χ QSM)

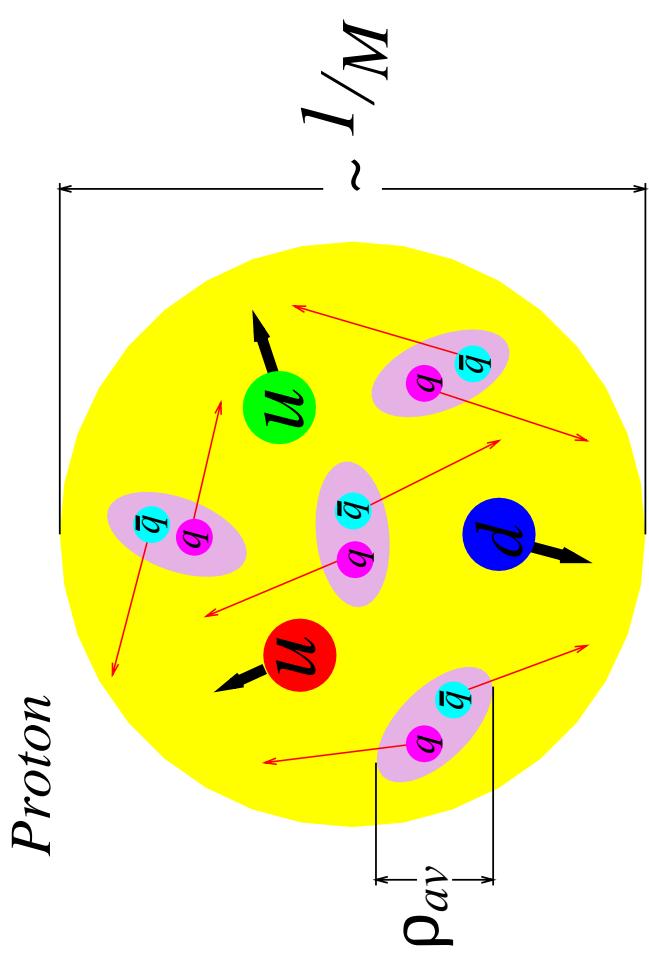


$$\langle p_T^2 \rangle_{\text{val}} \sim M^2$$

Picture with QCD vacuum effects

(from Dirac continuum ('sea') in χ QSM)

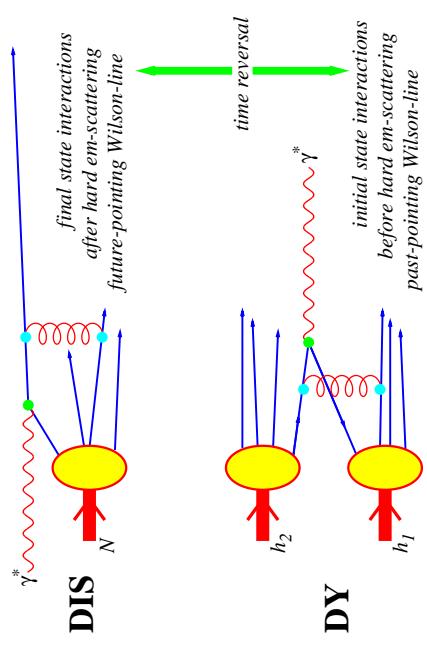
$$\begin{aligned}\langle p_T^2 \rangle_{\text{val}} &\sim M^2 \\ \langle p_T^2 \rangle_{\text{sea}} &\sim \rho_{\text{av}}^{-2}\end{aligned}$$



What we computed:

imagine you are a 'virtual photon'
you look for a q, \bar{q} to hit in the nucleon
→ 'primordial' p_T -distribution

effect of Wilson-lines ('ISI/FSI')
can compute in instanton vacuum
not yet done (on the agenda)



Conclusions

- basis for azimuthal and spin phenomena: **p_T -dependence of f_1^a !**
Gauss Ansatz useful effective tool (energy-dependence matters!)
- approximate Gauss-behavior for valence- q supported in quark models
(bag, covariant parton model, χ QSM)
- prediction from χ QSM: $\langle p_T^2 \rangle_{\text{sea}} > \langle p_T^2 \rangle_{\text{val}}$
- interplay of 2 scales: typical constituent quark scale $M \rightarrow \langle p_T \rangle_{\text{val}}$
short-range correlation scale $\rho_{\text{av}}^{-1} \rightarrow \langle p_T \rangle_{\text{sea}}$
- prediction from QCD vacuum structure & chiral symmetry breaking
consequences observable \rightarrow **future data** (JLab12, COMPASS, EIC)

Thank you

Support slides

Example 3: p_T in Hall-C

π^\pm from proton/deuteron

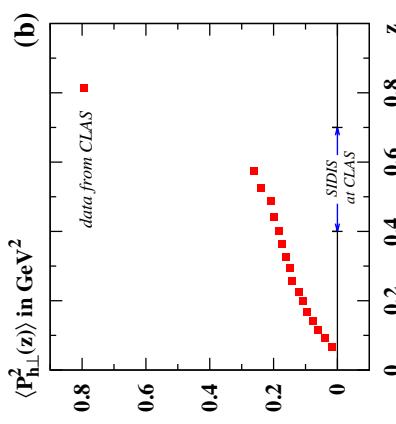
$$\langle x \rangle = 0.32, \langle z \rangle = 0.55$$

$$2 \text{ GeV}^2 < Q^2 < 4 \text{ GeV}^2$$

Gaussian widths

- flavor-independent!

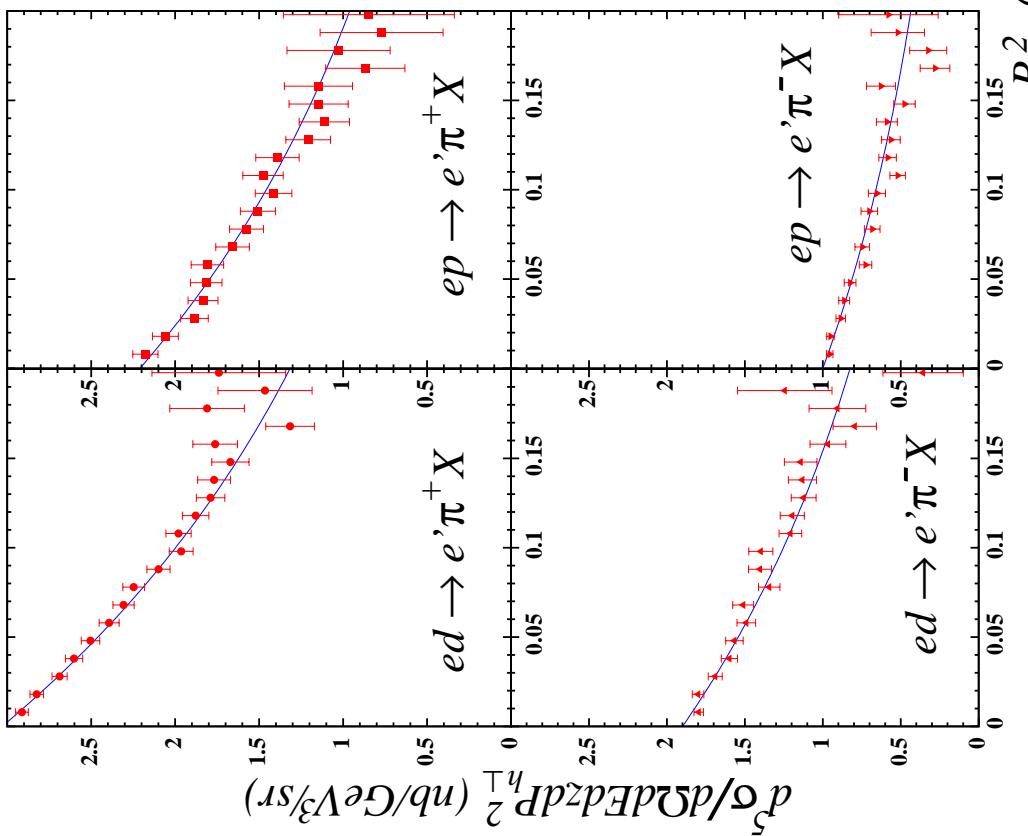
- not fitted,
but taken
from CLAS:



Osipenko et al

CLAS, Hall-C, Gauss

all compatible!



Mkrtchyan et al, PLB 665, 20 (2008)
seen "indications" for flavor-dep. of $\langle p_T^2 \rangle$, $\langle K_T^2 \rangle$
only due to included higher twists ('Cahn effect')

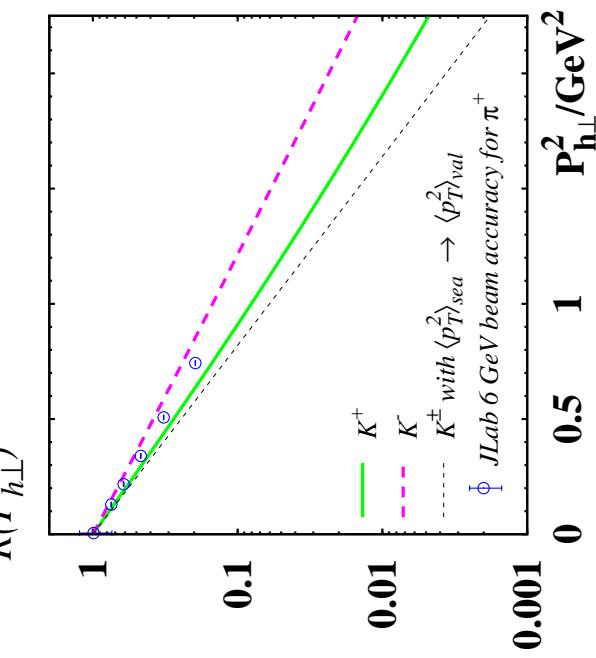
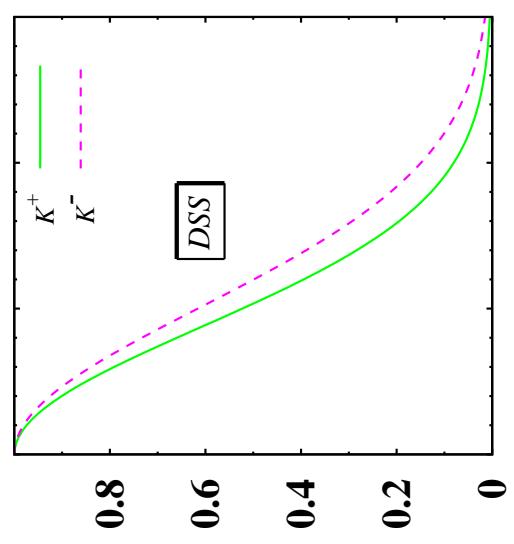
Prediction for JLAB12

if $\langle p_T^2 \rangle_{\text{sea}} = \langle p_T^2 \rangle_{\text{val}}$ $\Rightarrow P_{h\perp}$ -dependence of σ^{K^+} and σ^{K^-} the same

if $\langle p_T^2 \rangle_{\text{sea}} \neq \langle p_T^2 \rangle_{\text{val}}$ \Rightarrow they are different:

$$R(P_{h\perp})$$

$$(a)$$



$$R(P_{h\perp}) \equiv \frac{d\sigma_{UU}(P_{h\perp})/dP_{h\perp}}{d\sigma_{UU}(0)/dP_{h\perp}}$$

$\langle p_T^2 \rangle_{\text{sea}} - \langle p_T^2 \rangle_{\text{val}}$ from chiral quark soliton model
 DSS = de Florian, Sassot, Stratmann, PRD **75**, 114010 (2007)

if at JLab12, EIC kaons
 as prolific as π^\pm at JLab6
 → clear measurement